WHAT EUROPA'S IMPACT CRATERS REVEAL: RESULTS OF NUMERICAL SIMULATIONS.

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Introduction: Europa's surface is only lightly cratered; 28 primary impact structures larger than 4 km in diameter have been identified [1]. Nonetheless, the craters span a wide range of sizes (up to ~50 km diameter) and exhibit morphologies similar to those observed on other planets, following a progression generally correlated with crater size [1-3]. Primary craters less than ~5 km in diameter, have the bowl shape typical of simple craters. Craters ~5-24 km in diameter have flat floors and several have central peaks [1-4], characteristics typical of complex craters, although Europa's craters tend to be shallower [1-3]. Two larger impact structures, Tegid and Taliesin, appear to have unusual morphologies, but have been imaged only at low resolution and so are poorly understood. The two largest impact structures, Callanish and Tyre, consist of disrupted centers ringed by numerous concentric graben with diameters of up to 100 km.

The morphology of a crater is influenced by the energy of the impact event (related to crater size) as well as by the gravity, material properties and near-surface structure of the target. So, the characteristics of impact craters can be used to infer information about the target. For example, the diameter of the simple-to-complex transition depends upon the strength of the target material [*e.g.*, 5]; Europa's anomalously shallow craters [1-3] may be a result of the collapse process itself under Europan conditions or of post-impact viscous relaxation; and the concentric fractures around the two largest impact structures may have formed as a result of Europa's near-surface structure [*e.g.*, 6]. Therefore, careful study of craters can reveal much about the nature of Europa's near-surface.

One approach to investigating the constraints that the observed crater morphologies put on Europa's near-surface structure is to use numerical methods (*e.g.*, hydrocode and finite-element modeling) to simulate impact cratering under Europan conditions. By reproducing the observed crater morphologies it is possible to constrain the near-surface structure and conditions.

Several discrete lines of evidence [*e.g.*, 7-10] suggest that Europa's icy surface is but a thin shell overlying a liquid water ocean. Although the total thickness of Europa's outer H_2O layer is constrained by gravity measurements to be 80-170 km [11], estimates for the thickness of the solid ice range from only a few [*e.g.*, 12-15] to a few tens of kilometers [*e.g.*, 16-18].

Although Europan complex craters are shallow, they otherwise resemble complex craters found elsewhere in the solar system; their central peaks are morphologically similar to those observed on other planets. Therefore, the simplest explanation is that they formed by the same mechanism. In lunar and terrestrial craters central peaks consist of deeply buried material that was uplifted during crater formation [19,20]. Therefore, their occurrence on Europa requires that the ice shell not be breached during crater formation. So, numerical simulations of impact cratering in ice layers of various thicknesses overlying liquid water can provide constraints on the thickness of Europa's ice shell.

Modeling impact-induced melting and vaporization: Turtle and Pierazzo [4] conducted hydrocode simulations of vapor and melt production during impacts into ice layers with various thicknesses and thermal gradients overlying liquid water; complete vaporization or melting penetrating to liquid water or warm ice would preclude the formation and preservation of central peaks, therefore these models can constrain the thickness of Europa's crust. Turtle and Pierazzo [4] simulated impacts that would produce transient craters with diameters of ~12 and ~21 km (Fig. 1), lower limits for the transient crater diameters predicted for Europa's largest central peak crater (Pwyll) and the multiple-ring craters, respectively [1]. Their simulations demonstrated that at the times and locations of complex crater formation on Europa, the cold ice layer had to exceed 3-4 km [4]. Impacts disrupt target material well beyond the zone of partial melting [*e.g.*, 5], so these simulations put a lower limit on the thickness of the ice.

Modeling crater collapse: Turtle and Ivanov [21] conducted hydrocode simulations of the excavation and collapse of 10-km-diameter transient craters (within the range expected for Europa's central peak craters [1]) in ice layers 5-11 km thick with linear thermal gradients. They found a strong dependence of crater morphology on ice thickness (Fig. 2). For ice less than ~8 km thick, liquid water penetrated to the surface as the transient crater collapsed, precluding central peak formation. Therefore, these simulations provided a lower limit for the thickness of the Europan ice at the times and locations of central peak crater formation. To prevent craters from penetrating to an ocean, the ice shell thickness must be comparable to of greater than the transient crater diameter: 10-15 km thick. This range is consistent with Schenk's [2] results based on the diameters at which Europa's craters are observed to undergo morphologic transitions.

Conclusions: Numerical modeling of impact cratering is a powerful tool for constraining the properties of Europa's near-surface. Further modeling to investigate the later stages of cratering, including the formation of rings around Callanish and Tyre, as well as longer term modification due to viscous creep is currently underway and promises to reveal yet more information about Europa's near-surface.

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Fig. 1: Melting and vaporization [from 4] in large (A, B, C) and small craters (D, E, F) in: 9 km of ice over liquid water (A, D); 5 km of ice over liquid water (B, E); and a 3 km thick conductive lid over convecting ice (C, F). Solid, dotted, and dashed lines circumscribe the regions of complete vaporization, complete melting, and 50% melting.

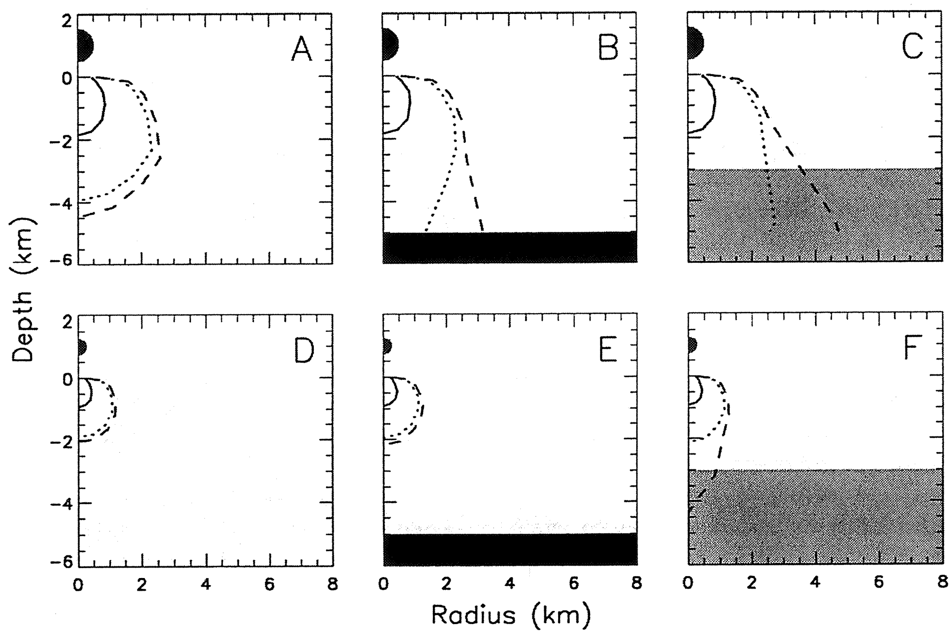

Fig. 2: Cross-sections of the final stages of simulations of impacts in ice 5, 6, 7, 8, 9, and 11 km thick (from upper left to lower right) illustrating penetration of water to the surface during crater collapse in ice ≤7 km thick [from 21].